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NASA TECHNICAL MEMORANDUM

~~NASA TM-88008~~ P 45

NASA-TT-20040

# PRELIMINARY STUDY OF AN APPARATUS TO CONTROL THE TEMPERATURE OF THE FLOW ENTERING THE T2 CRYOGENIC WIND TUNNEL

J. Gobert and J. Breil

Translation of ETUDE PRELIMINAIRE D'UN DISPOSITIF DE CONTROLE DE LA TEMPERATURE DE L'ECOULEMENT DESTINE A LA SOUFFLERIE CRYOGENIQUE T2, ONERA-CERT R.T. OA 20/5007, April 1983 37 pp.

N87-26052

(NASA-TT-20040) PRELIMINARY STUDY OF AN APPARATUS TO CONTROL THE TEMPERATURE OF THE FLOW ENTERING THE T2 CRYOGENIC WIND TUNNEL (NASA) 43 p Avail: NTIS HC A03/MF A01 CSCL 14B G3/09 Unclas 0004991

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON D.C. 20546 MARCH 1987

STANDARD TITLE PAGE

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| ~~NASA TM 88500~~ NASA-TT-20040 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| PRELIMINARY STUDY OF AN APPARATUS TO CONTROL THE TEMPERATURE OF THE FLOW ENTERING THE T2 CRYOGENIC WIND TUNNE. | March 1987 |
| | 6. Performing Organization Code |

| 7. Author(s) | 8. Performing Organization Report No. |
|---|---|
| J. Gobert and J. Breil | |
| | 10. Work Unit No. |

| 9. Performing Organization Name and Address | 11. Contract or Grant No. |
|---|---|
| Leo Kanner Associates<br>Redwood City, California 94063 | NASW-4005 |
| | 13. Type of Report and Period Covered<br>Translation |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration, Washington D.C. 20546 | 14. Sponsoring Agency Code |

15. Supplementary Notes

Translation of ETUDE PRELIMINAIRE D'UN DISPOSITIF DE CONTROLE DE LA TEMPERATURE DE L'ECOULEMENT DESTINE A LA SOUFFLERIE CRYOGENIQUE T2.

16. Abstract

The use of cryogenic blast wind tunnels reveals the need to control the flow parameters: temperature, pressure, speed. This report gives the results of a preliminary study conducted on the T'2 wind tunnel of CERT. Its purpose is to show the feasibility of controlling the temperature with a real time mini-computer.

| 17. Key Words (Selected by Author(s)) | 18. Distribution Statement |
|---|---|
| cryogenic wind tunnel - blast wind tunnel transonic wind tunnel - temperature control - digital regulation - process control. | Unclassified-Unlimited |

| 19. Security Classif.(of this report) | 20. Security Classif. (of this page) | 21. No. of pages | 22. |
|---|---|---|---|
| Unclassified | Unclassified | 38 | |

## Annotations

| | |
|---|---|
| $P_i$ | Generating pressure |
| $P_{iv}$ | Impact pressure measured in the tranquilization chamber |
| $P_{sv}$ | Static pressure in the test section |
| $Q_j$ | Injected air flow |
| $P_j$ | Injection pressure in the vanes of motor bend |
| $Q_{jLN_2}$ | Flow rate of injected liquid nitrogen |
| $P_{jLN_2}$ | Injection pressure of liquid nitrogen measured between the flushing tank and the wind tunnel at the injector level |
| $Q_e$ | Flow rate of gaseous mixture discharged |
| $M_v$ | Test section Mach |
| $Ti_v$ | Impact temperature measured in the tranquilization chamber |
| $Ti_c$ | Impact temperature measured in bend no. 2 |
| $T_j$ | Temperature of the injected air |
| $a_v$ | Section of the test air flow |
| $a_c$ | Section of the downstream neck |
| $P_{res}$ | Pressure of the air tank supplying the injection |
| $S_j$ | Total section of the air injection vanes |
| $S_m$ | Section of the circuit at the air injector level |
| $\lambda$ | Ratio $\frac{S_m}{S_j}$ |
| $U_{jLN_2}$ | Control for opening the $LN_2$ injection valves |
| $U_j$ | Control for opening the air valve |
| $U_e$ | Control for opening the discharge valves |
| $H_{LN_2}$ | Enthalpy of liquid nitrogen |
| $U_j$ | Control for opening the air valve |
| $U_e$ | Control for opening the discharge valves |
| $H_{LN_2}$ | Enthalpy of liquid nitrogen |

$C_p$ Specific heat of air

$\Phi$ Heat losses along the circuit

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# STUDY OF AN APPARATUS TO CONTROL THE TEMPERATURE OF THE FLOW ENTERING THE T2 CYROGENIC WIND TUNNEL

J. Gobert, J. Breil

## INTRODUCTION

/7*

The search for high Reynolds number for wind tunnel tests recently led to the development of cyrogenic wind tunnel projects in which the Reynolds number is increased by decreasing the flow temperature.

Among these projects, ONERA decided to transform the T2 wind tunnel of DERAT by adding a high quality internal insulation and a liquid nitrogen injection system. This new design will provide a new parameter since the temperature may be altered for values of up to nearly 100 K. Under these conditions, the operating point may vary in pressure and in temperature for a given Mach number.

This does not mean that there are no problems involved in obtaining a flow that is reproducible and stable throughout the test cycle at the desired temperature and pressure values.

In this light, DERAT designed a preliminary study of a device for controlling the liquid nitrogen system in order to quickly reach the desired temperature and to adjust it during a blast. The experimental part of this study was conducted on DERAT's T'2 wind tunnel which consists of a 1/4 scale model of the T2 wind tunnel. A follow-up study will be devoted to the control of the system for discharging the air-nitrogen gaseous mixture in order to regulate the operating pressure and to study potential couplings between the two parameters, temperature and pressure.

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*Numbers in the margin indicate pagination in the original text.

## 1 - DESCRIPTION OF THE AERODYNAMIC CIRCUIT OF WINDTUNNEL T'2

Figure 1 represents the aerodynamic circuit of windtunnel T'2. It is an induction wind tunnel with a return circuit which operates similar to that of the blast type wind tunnel (Ref. 1).

The flow is promoted by injecting air at high speeds (Mach 1.6) at the leading edges of the two vanes of bend no. 1 placed downstream from the test section. These jets with high impact pressures mix quickly with the induced flow and give the energy needed for compensating the entire load loss of the circuit.

Downstream from the motor bend, we find the liquid nitrogen injection device which will be described in more detail in the rest of the study.

In order to maintain a constant pressure in the test section throughout the blast, it is necessary to remove the same amount of air-nitrogen gaseous mixture as that injected. This removal is carried out through a part with permeable walls, located between the test section and the air injector bend.

The test section , which is 0.094 x 0.095 $m^2$, is equipped with solid walls. A sonic neck located right below it is used to set the Mach number. During the testing for this study, the Mach number was 0.76.

The circuit, constructed with ordinary steel, was provided /8 with internal insulation using cork plates 3 mm thick. Only the permeable discharge part was not insulated. The two vales of the first bend (air injector) are insulated with cork 1 mm thick.

## 2 - DEFINING THE PROBLEM

The operating point ($T_i$, $P_i$, $M_v$) essentially depends on four

variables:

-the injected air flow rate $Q_j$;
-the injected liquid nitrogen flow rate $Q_{jLN_2}$;
-the flow rate of the gaseous mixture $Q_e$ discharged;
-the ratio of the test section to that of the neck: $\frac{a_v}{a_c}$

These four magnitudes make it possible to vary the operating point according to the test requirements. $Q_{jLN_2}$ is used for regulating the temperature $T_i$, $Q_j$ and $Q_e$ the pressure $P_i$ and $Q_e$ and $a_v/a_c$ the Mach number. However, the action of each of these parameters is related to the values of the three others. Moreover, other less defined, or uncontrolled parameters also have an influence. We will mention among others:

-the temperature $T_j$ of the injected air;
-the heat losses $\phi$ along the circuit;
-the presence of a model in the test section;
-the presence of a pressure or temperature scan in the test section or downstream neck;
-the use of permeable walls;
-...

Under these conditions, it is difficult to predetermine the values of the four control magnitudes. One possible solution consists of guiding them in a closed loop throughout the blast.

In this phase of the study, we were primarily concerned with the temperature. This consisted of controlling the liquid nitrogen flow rate, with the other parameters being fixed.

Afterward, it will be necessary to control all of these four magnitudes based on the couplings of their actions. The operating range of the T2 wind tunnel is from 100 K to ambient temperature for a pressure of up to 5 bars and Mach numbers between 0.3 and 1.

## 3 - STUDY OF THE LIQUID NITROGEN INJECTION DEVICE /9

### 3.1. Description

For the study requirements, the T'2 wind tunnel was equipped with a liquid nitrogen injection system of a design patterned after that of the T2.

This system is installed immediately downstream from the air injector bend. This layout was retained to obtain better evaporation and a better air-nitrogen mixture (high speed and strong turbulence zone, maximum distance relative to the test section).

The injection part is represented in figure 2. It is a ring system made up of eight peripheral injectors (photo 1). The flow rate of each injector is controlled individually by means of a hit or miss electrovalve. The size of the injectors was selected to obtain a flow distribution forming a geometric progression of 2. The system can be related to a numerical valve.

The system was defined to obtain 64 ($2^6$) flow levels using 6 elementary flows. The latter two levels (high values) consist of two diametrically opposite injectors to improve the symmetry of the flow. Actually a few tests performed with a device with 6 independent injector gave encouraging results, but reveal a strong dissymetry in the geometrical distribution of the temperature, especially when using strong flows.

The table of figure 3 gives the respective theoretical flows of each injector as well as the manufacturer's references (Spraying Systems).

Figure 4 gives the theoretical flow curve. This curve reveals the nonlinearities due to quantification.

Figure 5 represents all services allowing the injectors to

operate. This device is patterned after that retained on the T2 wind tunnel (32 injectors).

3.2. Controlling the $LN_2$ Injection System

For this type of problem, it is difficult to predict in advance the control algorithm which will give the best results. Further, it is necessary to provide T2 tests with a model. Moreover the presence of this model and the problem of establishing its temperature will seriously complicate the blast development. Accordingly, it was already planned to cool the model before the blast outside the wind tunnel. Then a special test initiation procedure shall be developed. The burst will begin at a low Mach and at a low pressure, but at the desired temperature. When this temperature is reached, the model will be inserted into the wind tunnel using special equipment. Then the Mach number and the pressure will be increased to their target values while holding the temperature constant. Figure 6 gives a time diagram for such a procedure.

In order to retain maximum capabilities and flexibility for /10
the future, it was decided to manage the different controls (air liquid nitrogen and discharge flow rates) by a mini-computer which, may then take over complementary tasks such as controlling the section of the downstream neck and the temperature rise sequence and the model displacement.

Among the advantages of this solution, we will mention:

-the capability of developing any controls selected in advance by the user for an open loop;

-the capability of developing controls for a closed loop according to an algorithm which may be reevaluated as the results are acquired.

Although such a technique seems more complex at first than a solution developed around more conventional devices such as a wired squencer connected to analog regulators, it should be more performing and offer more flexibility in adapating to future requirements.

In the tests performed for this study, we used the acquisition chain of the T2 wind tunnel/ Ref. 2/ equipped with a HEWLETT-PACKARD 21 MX mini-computer (fig. 7) for controlling the liquid nitrogen injection valves in real time and for measurement acquisition. The interfacing of the injection system was accomplished simply using a digital input-output card of 16 parallel bits. The link which uses static power relays was made according to the diagram of figure 8. The different ways of opening and closing the electrovalves are obtained by an appropriate programmed coding.

### 3.3. Calibration of the Liquid Nitrogen Injection System

The purpose of this operation is to define a transfer function of the injection system in a steady state, i.e. to know the law relating the flow rate of the injected liquid nitrogen with the valve opening.

The nitrogen flow into an injector is governed by the law:

$$dp + \rho v dv = 0$$

As liquid nitrogen is incompressible, we may integrate the equation, which leads to:

$$P + \rho \frac{v^2}{2} = Cte = P_i$$

If S is the section of the injector, we have:

$$q = \rho S v = 2 S \sqrt{\rho_{LN_2}} \sqrt{P_i - P}$$

$$q = \rho S v = 2 S \sqrt{\rho_{LN_2}} \sqrt{P_{jLN_2}}$$

$P_i$ is the generating pressure of liquid nitrogen, P is the static pressure of the wind tunnel at the level of the nitrogen injection part.

If we let $U_{LN_2}$ be the control applied to the liquid nitrogen injection valves, we may express in the linear hypothesis:

$$S = k\, U_{LN_2}$$

We may therefore express a transfer function in the form:

$$\frac{Q_{LN_2}}{U_{LN_2}} = k \sqrt{\rho_{LN_2}} \sqrt{P_{jLN_2}} = K \sqrt{P_{jLN_2}}$$

by letting:

$$K = k \sqrt{\rho_{LN_2}}$$

Figure 9 gives a diagram of this transfer function.

The tests were conducted to check the validity of this transfer function and to determine the value of the coefficient K. To do this, a venturi flow meter was installed on the general power supply line of the liquid nitrogen injection system. Figure 10 gives the result of a test conducted to determine the real flow rates of each injector. To improve the accuracy, injector no. 1 remained open during the test in order to use the flow meter in its measuring range.

This calibration calls for a comment:

Injectors 1 and 5, although of the same type, give relatively different flow rates (the difference is greater than the system resolution). Conversely, injectors 3, 4 and 7 give very similar flow rates. A linearization solution by digital coding at the

control level was adopted. Two levels were disabled to eliminate the difference between the flow rates of injectors 4 and 5. We took advantage of the small difference between 3, 4 and 7 to code the 62 remaining levels on 8 bits ($2^6$ possible levels), by trying to avoid large transitions on the levels consisting of similar injectors. This solution resulted in a considerable time gain during the feasibility study conducted at T'2, but should not be retained for the T2 wind tunnel upon which 32 electrovalves are provided. One such linearization would risk penalizing the control mini-computer too much. Figure 11 shows the curve for the flow rates obtained by making a ramp on the control with this type of linearization. Tests conducted with different values for the liquid nitrogen injection pressure showed that the characterization retained for the transfer function is valid as soon as this pressure exceeds about 5 bars.

It is important to note that during the tests conducted for these calibrations, initiation problems appeared when the small injectors were opened. This was probably due to the presence of gaseous plugs. These problems were partially solved by a very good outside insulation of the entire injection system as well as by first placing the injectors systematically into cold conditions.

## 4 - ESTABLISHING A MATHEMATICAL MODE FOR THE WIND TUNNEL /12

This does not involve an in-depth study of physical phenomena governing the flow in the wind tunnel during a test. The purpose is to find mathematical relationships relating the output values with those of the inputs of the process to be controlled. The set of these relations forming the model should be as simple as possible to facilitate the future establishment of control laws. As the model is subjected to the same inputs as the wind tunnel, it should see its outputs follow the same pattern as those of the wind tunnel with an acceptable error. The control laws will be caclulated and prepared to control the model quasi perfectly. As the system is developed in a closed loop, it should

to correct the errors caused by differences between the model and the real process. This shows that the model will be exact, and the control laws will be performing. Too much simplification of the model or an incorrect representation may lead to an unacceptable operation. It is therefore necessary to reasses the initial characterization. It is this final behavior which enables the starting hypotheses to be verified.

First, it is possible to begin with the characterization shown in figure 12. This characterization is based directly on what was described in section 2. Also, the element representing the wind tunnel may be divided into two parts: the first governing the equilibrium state in the absence of input changes, the second expresses the dynamic changes at the outputs in the presence of an input variation. This is shown in figure 13. We recall that we are primarily interested here in the temperature and in the liquid nitrogen flow rate.

## 4.1. Study of the Steady State

On each point of the circuit and at each instant, the state of the moving fluid is described by local unsteady equations giving the variation of the mass, of the dynalpy and of the energy (Ref. 2). If the flow is assumed to be one-dimensional, these equations are expressed:

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x}(\rho u\omega) = m'$$

$$\frac{\partial}{\partial t}(\rho u\omega) + \frac{\partial}{\partial x}(P + \rho U^2)\omega) = P\frac{\partial \omega}{\partial x} + j' - f'$$

$$\frac{\partial}{\partial t}(\rho h_i \omega) + \frac{\partial}{\partial x}(\rho u\omega\, h_i) = \frac{\partial}{\partial t}(P\omega) + \phi'$$

with $\omega$ : section of the circuit is assumed to be constant
$m'$: mass variation per unit of length
$j'$: dynalpy variation per unit of length
$\phi$ : heat flux per unit of length
$f'$: heat losses per unit of length

If we assume that the flow rate, the enthalpy and the impact pressure are independent from the longitudinal position along the circuit, i.e. V is the volume of the wind tunnel and L the length of the circuit, we have, at each instant:

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$$V \frac{d\rho}{dt} = Q_j + Q_{LN_2} - Q_e \quad (1)$$

$$L \frac{dq}{dt} = J - F \quad (2)$$

$$\frac{V}{\gamma - 1} \frac{dp}{dt} = Q_j H_j + Q_{LN_2} H_{LN_2} - Q_e H_e + \text{Losses} \quad (3)$$

Given a steady state, we have:

-according to (1): $Q_e = Q_j + Q_{LN_2}$

-according to (3): $Q_j C_p T_j + Q_{LN_2} H_{LN_2} - Q_e C_p T_i + \text{Losses} = 0$

by assuming that gas is discharged at temperature $T_i$.

By removing $Q_e$ between the two equations, we have:

$$T_i = \frac{Q_j C_p T_j + Q_{LN_2} H_{LN_2} + \text{Losses}}{C_p (Q_j + Q_{LN_2})}$$

If we disregard the losses, the liquid nitrogen flow rate required for cooling the motor air is given by:

$$Q_{LN_2} C_p = Q_j \frac{(T_j - T_i)}{(T_i - \frac{H_{LN_2}}{C_p})}$$

If all inputs are fixed except that used for regulating the liquid nitrogen flow rate, the measurement of the injection pressure in the vanes of the motor bend makes it possible to calcualte this flow rate.

We have: $$Q_j = \frac{0.0404 \, S_j \, P_j}{\sqrt{T_j}}$$

The liquid nitrogen injection device has a virtually linear response (section 3), we therefore have:

$$Q_{LN_2} = K \cdot \sqrt{P_{jLN_2}} \; U_{LN_2}$$

K: slope of the straight line for $P_{jLN_2}$

We may therefore derive the value of the theoretical control for a desired temperature $T_{iv}$ as a function of the directly measurable magnitudes.

## 4.2. Study of the Transient State

### 4.2.1. Experimental Qualitative Study

To have a glimpse of the behavior of the system in transient state, a few experiments were conducted in which the flow rate of of injected nitrogen was subjected to levels with a small amplitude (figure 14).

An examination of the curves recorded reveals several phenomena which may be broken down as follows: /14

a) Existence of a delay time tr on the temperature response to a nitrogen flow rate level.

b) At the end of time tr. the temperature response is not a front, but is close to the response of a first order system.

c) At instants 2 tr, 3 tr ..., a propagation effect appears which quickly attenuates.

To simpifly the problem, we will not account for the propagation effect and will will relate the system in a steady state

to a pure time delay and a time constant. Figure 15 gives the simplified transfer function which is results.

4.2.2. Theoretical Quantitative Study

Given the characterization just described, we are going to try to derive the theoretical values of the delay time tr and of the time constant $\tau$.

a) Delay Time

In the first approximation, the delay time may be considered to be the sum of the switching time of the liquid nitrogen injection and of the time it takes the gaseous particles to travel between between the injectors and the tranquilization chamber. A preliminary study was conducted to assess the valve opening and closing times which are about 0.25 s.

The propagation tim is the time required for the equivalent gas mass ($m_1$) to pass into the volume ($V_1$) located between the injectors and the tranquilization chamber in any section of the circuit. The flow rate is retained, we therefore consider the flow rate in the test section, after the neck is initiated:

We therefore have: $$t_{prop} = \frac{m_1}{Q} = \frac{V_1 \rho}{Q}$$

Moreover: $$Q = \frac{0{,}0404 \; P_{iv} \; a_v}{\sqrt{T_{iv}} \; \frac{a_v}{a_c}(M)}$$

with: $$\frac{a}{a_c}(M) = \frac{1}{M} \; \frac{(1 + 0{,}2\,M^2)^3}{(1{,}2)^3}$$

It is therefore possible to obtain the propagation time with measurable magnitudes ($P_{iv}$, $T_{iv}$, $M_v$):

$$t_{prop} = \frac{V_1 \rho_i \; \sqrt{T_{iv}} \; \frac{a}{a_c}(M)}{0{,}0404 \; P_{iv} \; a_v}$$

By introducing $\frac{P}{\rho} = r\,T$, the total delay time is expressed: /15

$$t_r = t_{valve} + t_{prop} = t_{valve} + \frac{V}{0{,}0404\ r\ a_v} \frac{1}{\sqrt{\tau_{iv}} \frac{a}{a_c}\ (M)}$$

b) Time Constant

We may rewrite the equations giving the variation of mass and of energy in one section of the circuit (equation (1) and (3) of section 4.1):

$$V \frac{d\rho}{dt} = Q_j + Q_{LN_2} - Q_e \qquad (1)$$

$$\frac{V}{\gamma - 1} \frac{dp}{dt} = Q_j H_j + Q_{LN_2} H_{LN_2} - Q_e H_e + \text{Losses} \qquad (3)$$

And $\frac{p}{\rho} = r\,T$ leads to $\frac{dp}{p} = \frac{d\rho}{\rho} + \frac{dT}{T}$

I.e.: $$d\rho = -\frac{\rho}{T} dT + \frac{1}{rT} dp$$

(1) may therefore be expressed:

By removing $\frac{dp}{dt}$ between (3) and (4), we have:

$$V\rho \frac{dT}{dt} + (Q_j + Q_{LN_2} - Q_e)\,T = \frac{\gamma - 1}{r} (Q_j C_p T_j + Q_{LN_2} H_{LN_2} - Q_e C_p T + \text{Losses}$$

If we deviate from the equilibrium state by a small variation of $Q_{LN_2}$, it may be assumed that the flow rate discharged remains close to that of the equilibrium state, i.e.:

$$Q_e = \frac{Q_j C_p T_j + Q_{LN_2} H_{LN_2} + \text{Losses}}{C_p T}$$

The equation therefore becomes

$$V\rho \frac{dT}{dt} + (Q_j + Q_{LN_2})T = \frac{Q_j C_p T_j + Q_{LN_2} H_{LN_2} +}{C_p}$$

As the variation $\Delta Q_{LN_2}$ is small compared to $Q_{LN_2}$, it may be assumed that the term $Q_j^2 + Q_{LN_2}$ varies little and T is a solution of a differential equation expressed:

$$V\rho \frac{dT}{dt} + (Q_j + Q_{LN_2})\, T = Cte$$

We know that the solution of such an equation is expressed:

$$T = T_o + \Delta T\, (e^{-t/\tau} - 1)$$

with:

$$\tau = \frac{V\rho}{Q_j + Q_{LN_2}}$$

## 5 - CLOSED LOOP TESTING CONDUCTED ON THE T'2 WIND TUNNEL /16

### 5.1. Regulation With a PID Type Algorithm Using the Temperature of the Second Bend

Since the measurement at the level of bend no. 2 was not assigned a long delay time ( < 10 ms), the temperature regulation at this level first seems easier to achieve using a conventional PID type algorithm than the temperature regulation in the tranquilization chamber.

We will quickly give the method used for determining the coefficients of the regulator. The transfer function of a PID type regulator (proportional-integral-derivative) is expressed:

$$H(p) = K\, (1) + \frac{1}{T_i p} + T_d\, p)$$

The values of K, $T_i$ and T are determined using an empirical method. Tests are conducted with $T_d = 0$ and $T_i \to \infty$, the value of K is increased until oscillations appear. This value of K is notated $K_c$ and the oscillation period is notated $T_c$. ZIEGLER and NICHOL's emprical formulas are therefore used. They are:

$$K = 0.6\ K_c$$
$$T_i = 0.5\ T_c$$
$$T_d = 0.12\ T_c$$

In the case of a PI type regulator ($T_d = 0$), we use:

$$K = 0.45\ K_c$$
$$T_i = 0.83\ T_c$$

Several tests were conducted for temperature values between 120 K and 200 K. In these tests, the sampling period was selected to be small enough (10 ms) compared to the system band width for the above relations to remain valid. In effect, these relations are normally used for analog type regulators that are therefore not sampled, but which still have a limited band width.

The regulation is correct as long as there is no switching reaching the high rate injectors. An example of the results obtained is given by the curve of figure 16.

Several points may be noted:

-The temperature fluctuation detected at the output of bend no. 2 is of the order of $\pm$ 1 degree; it is $\pm$ 0.25 degrees in the tranquilization chamber.

-There is a considerable temperature difference that is difficult to predict between the tranquilization chamber and the temperature of bend no. 2. This temperature difference is explained by the presence of a heat flux in the return circuit, with these fluxes decreasing in time.

-During a regulation involving a switching at the level of /17
heavy weight injectors, there is a disturbance probably caused

by a modification of the spatial temperature distribution at the output of the second bend which materializes by a variation of the temperature level in the tranquilization chamber for a given bend temperature (figure 17), which makes it even more difficult to predict the temperature variation between the bend and the tranquilization chamber.

Measurements performed with a plate including four thermocouples arranged at the output of the second bend showed that the flow at this point did not have a good temperature homogeneity and that the spatial distribution is a function of the injection configuration.

Tests were then conducted using the mean temperature of the four thermocouples to calculate the error signal at the PID input. These tests did not provide much improvement, as the flow was probably very inhomogeneous at this point.

## 5.2. Regulation Using the Temperature in the Tranquilization Chamber

### 5.2.1. Regulation with a PID Type Algorithm

The few tests conducted under these conditions showed that the longer delay time than previously (≃ 400 ms for a Mach number of 0.76) requires a considerable decrease in the regulator coefficients to avoid pumping, but they still prove that it is posisble to use the temperature of the tranquilization chamber to perform the regulation (figure 18).

The drawback of this system is the poor performance during start-up and in cases of any outside disturbance.

### 5.2.2. Improving the Control

To improve the temperature control, we made two major

modifications:

-increasing the sampling cycle (600 ms);
-predicting the error signal and its derivative after the delay time.

In effect, these two modifications are related to each other. The sampling period was increased to about 1 ½ the delay time. It was then possible by measuring the two points at instants t and $t^+ \Delta t$ to predict the value of the temperature at instant $t + t_r$ and to thus remove the effect of the delay time. This estimate uses the illustration given in the preceding paragraph and accounts for the value of the time constant $\tau$ calculated and the delay time $t_r$.

The coefficients of the regulator were modified to include the sampling cycle.

The tests conducted with this type of control (figure 19) /18 showed that the performance obtained during start-up is clearly improved, that the system stabilizes satisfactorily and that the precision obtained is correct ($\pm$ 0.5°). Further, the relatively long sampling cycle results in a fairly low fluctuation rate.

However, this method has a drawback: that of poor performance in the case of an outside disturbance, since the delay time requires that the effect of the sampling period be added when there is any reaction to an outside disturbance.

## CONCLUSION

These preliminary tests showed the feasibility of controlling the temperature on T'2 using a mini-computer. This study made it possible to approximate the problem and in particular to establish

a simple representation model which may be extrapolated for T2. Further, certain technological problems, particularly the impact of precooling the liquid nitrogen injection device, were revealed and solutions could be foreseen.

The transposition to T2 did not cause any major problems (Ref. 4 and 5). An equivalent study was undertaken to regulate the pressure at T'2. Care was exercised to avoid any coupling between the two regulations. For the future, the models obtained should make it possible to establish more sophisticated control laws than PID type regulations (optimal control for example). Further, the use of a second computer will make it possible to dissociate the control functions and to obtain measurements. Such a solution will increase the computer capacity in real time and thereby the control capabilities (temperature, pressure, Mach number, precooling and translation of the model, etc.) while retaining the current acquisition capabilities (processing in real time of data, testing with real time control of adaptable walls (Ref. 6).

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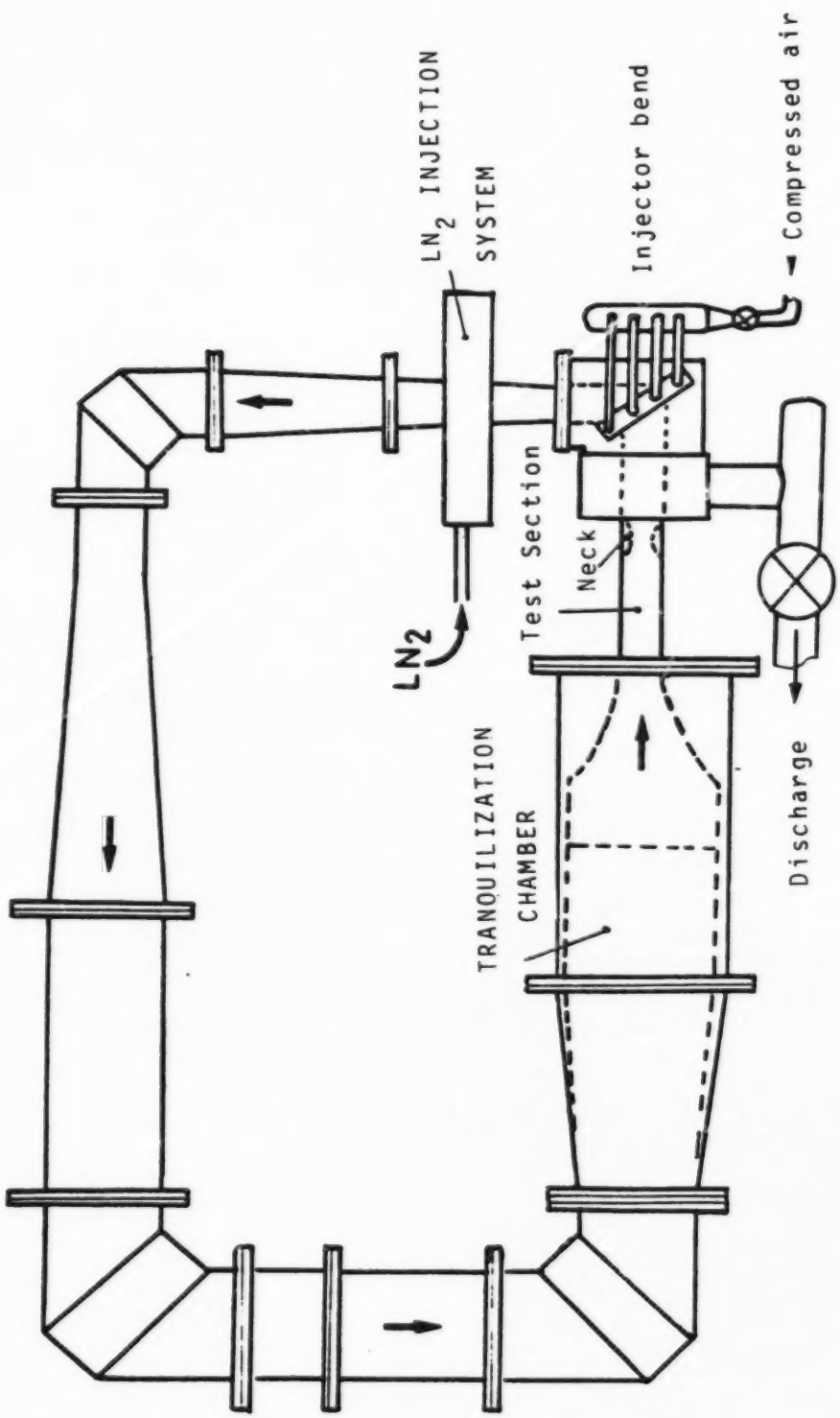


Fig. 1. Diagram of the aerodynamic circuit of wind tunnel T'2

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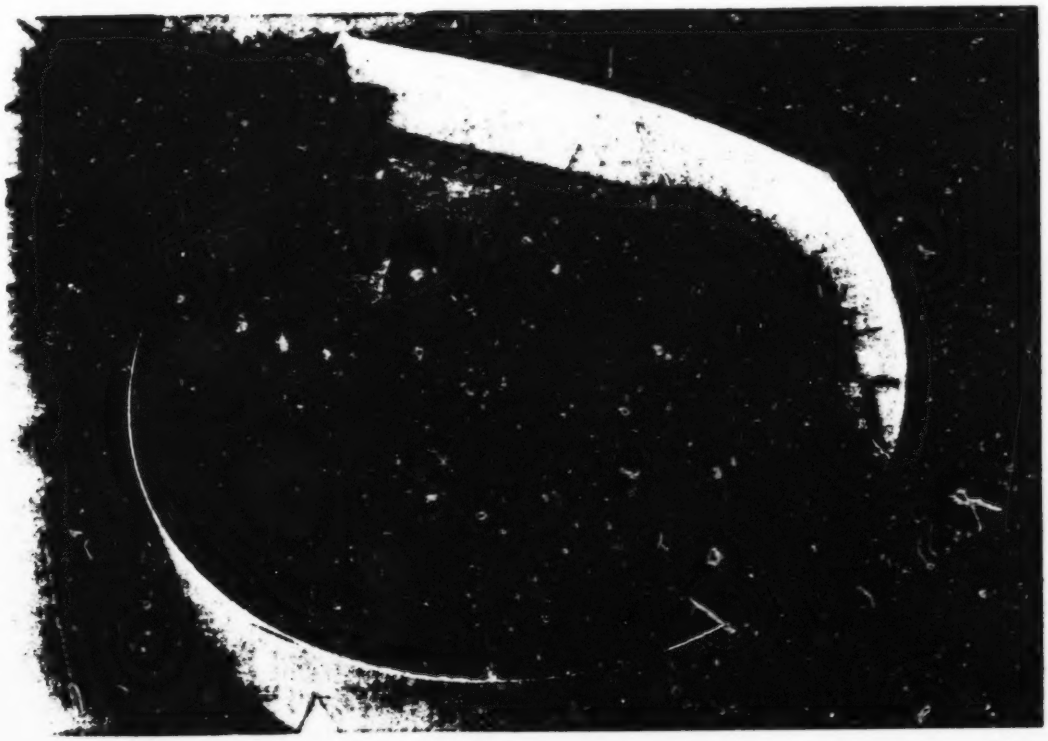

Overview of an LN2 injection system (8 injectors)

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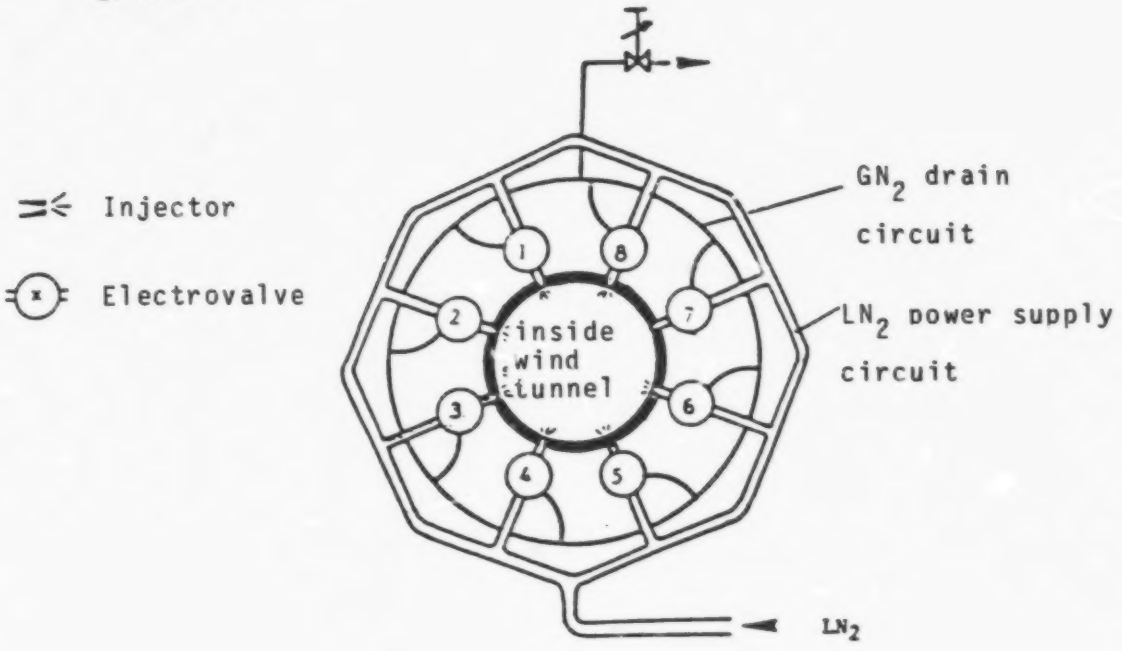



Fig.2. Diagram of liquid nitrogen injection system
$LN_2$

| Elementary levels | Number of injectors | Number of injectors s | Type of injectors | Theoretical flow (l/mn) |
|---|---|---|---|---|
| 0 | 1 | 6 | 9502 | 1,4 |
| 1 | 1 | 2 | 9504 | 2,9 |
| 2 | 1 | 8 | 9508 | 5,7 |
| 3 | 1 | 4 | 9515 | 10,7 |
| 4 | 2 | 3-7 | 9515 | 21,4 |
| 5 | 2 | 1-5 | 9530 | 42 |

Fig.3. Organization of liquid nitrogen injection system

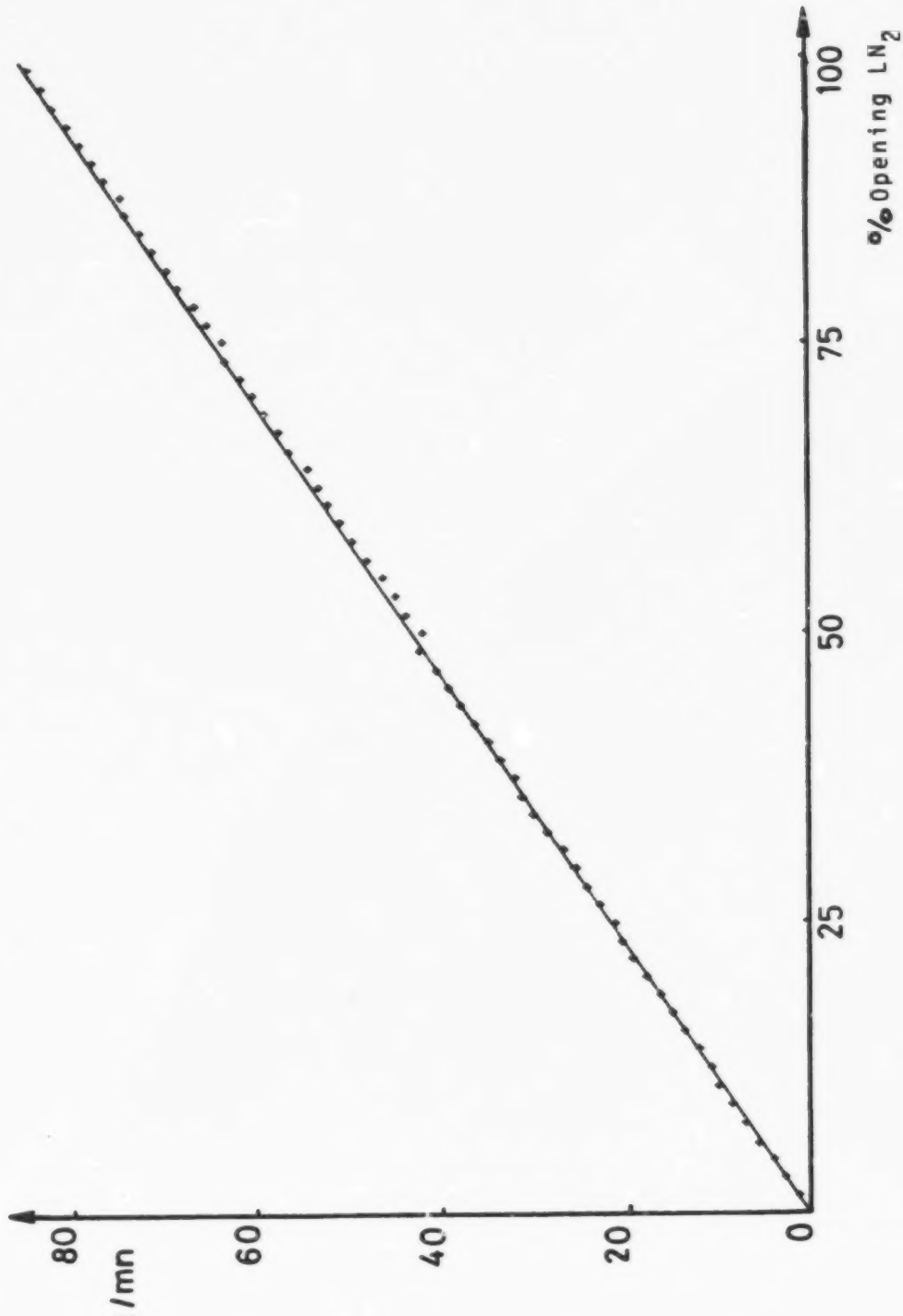





Fig.4. Curve of theoretical flow rates as a function of the opening

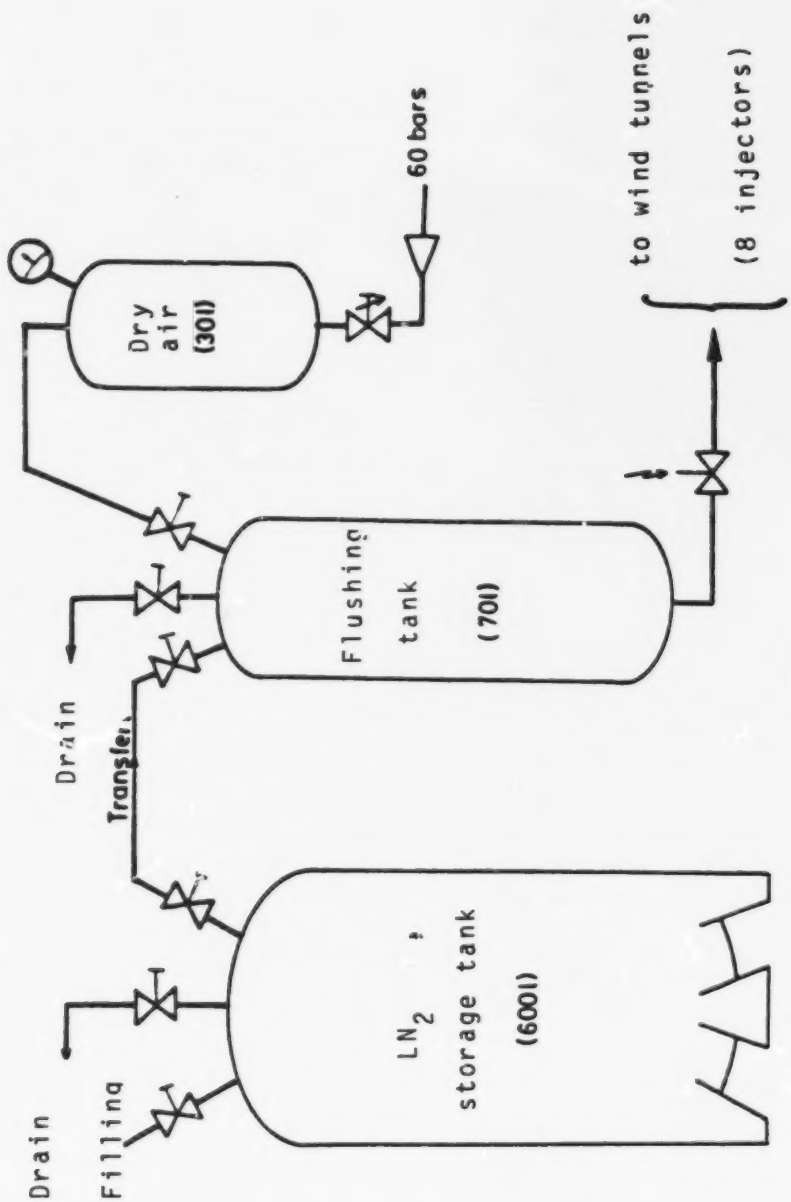
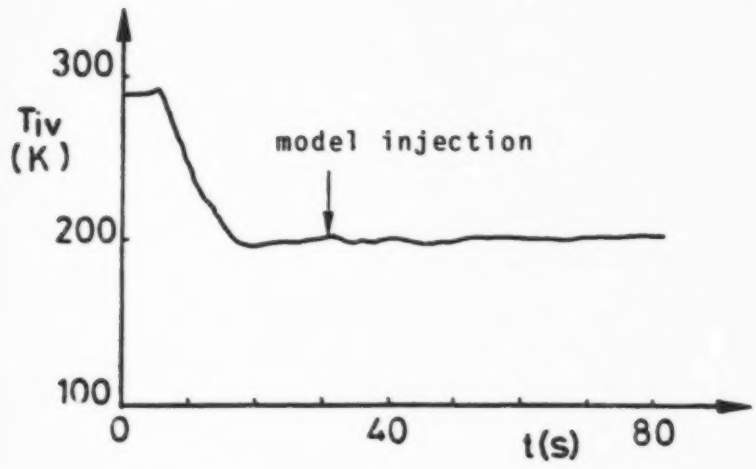
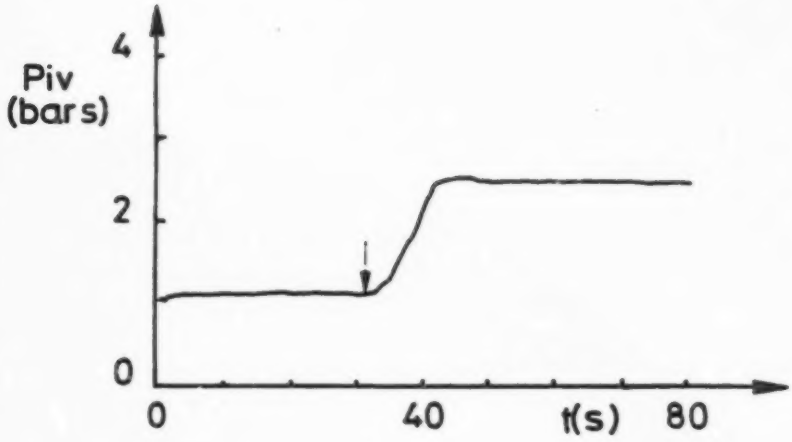



Fig.5. Diagram of injection system equipment $LN_2$



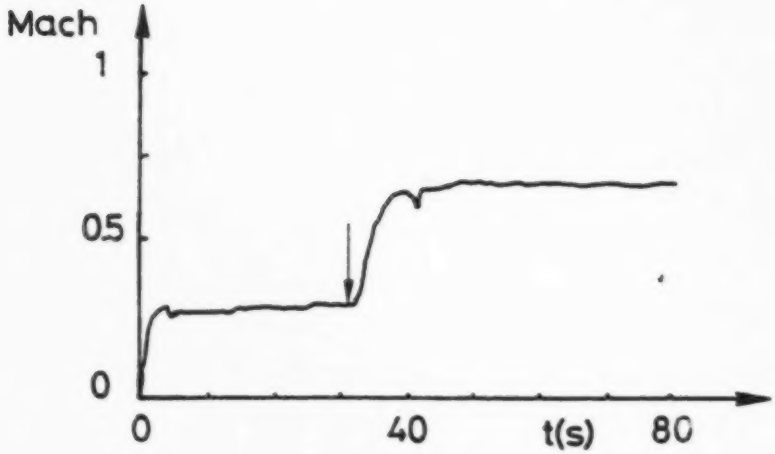






FIG. 6 - Test time on T2 with model

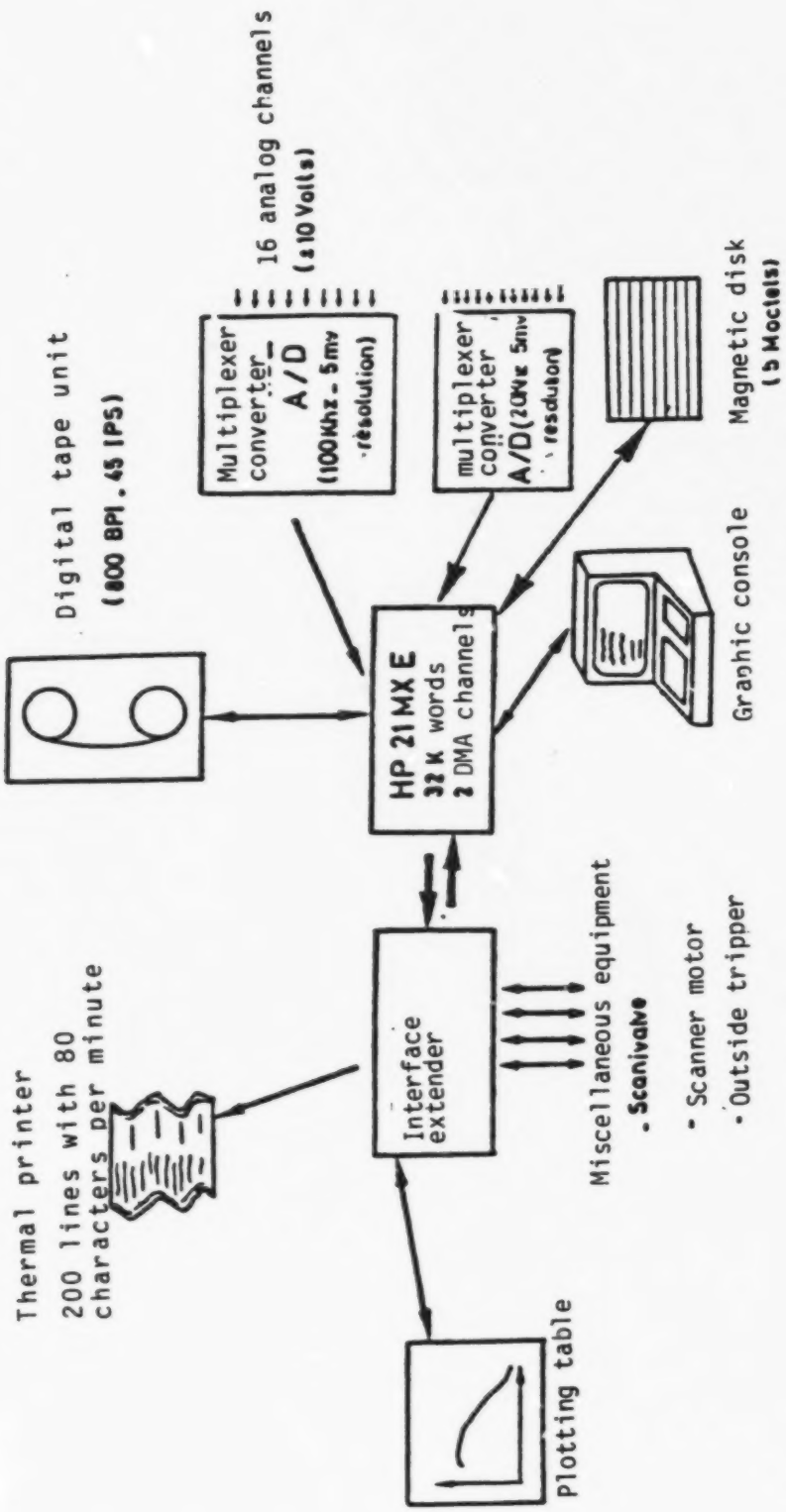



Fig.7. Acquisition chain of the T2 wind tunnel

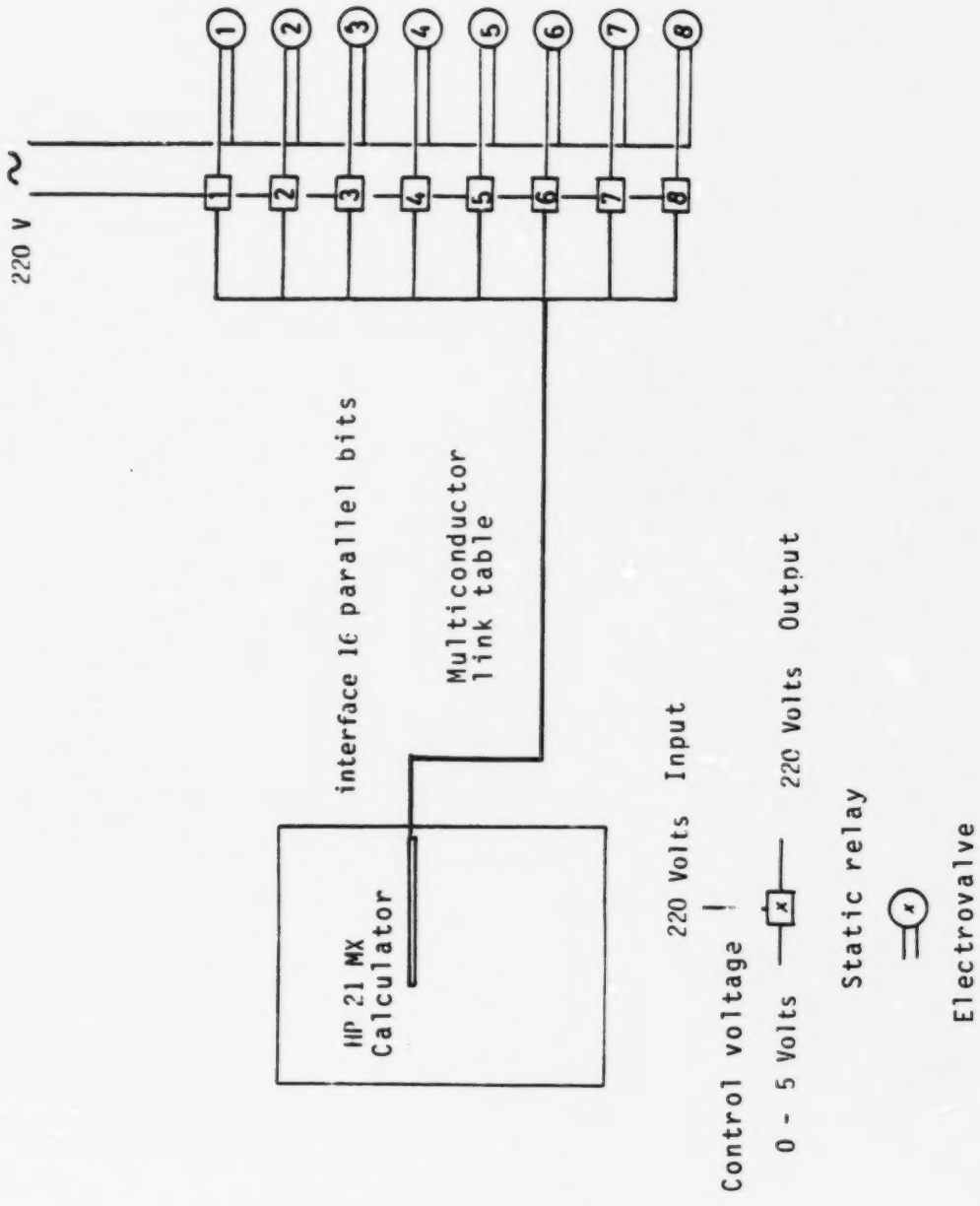



Fig.8. Interfacing of liquid nitrogen injection valves

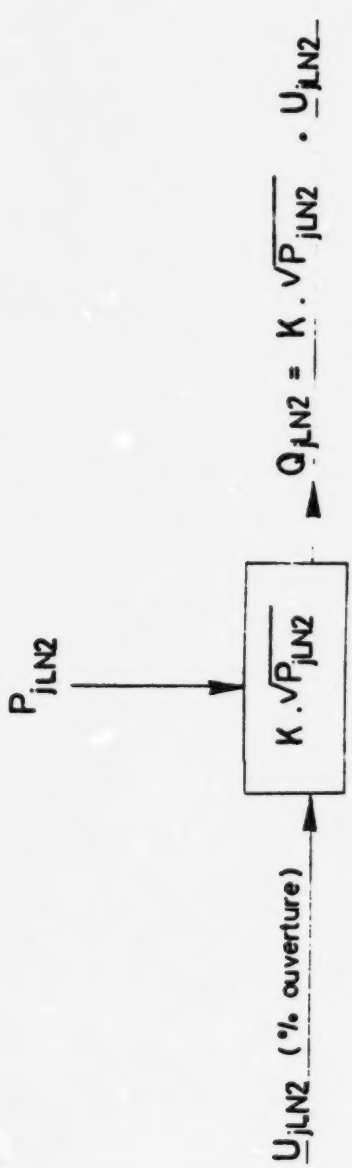
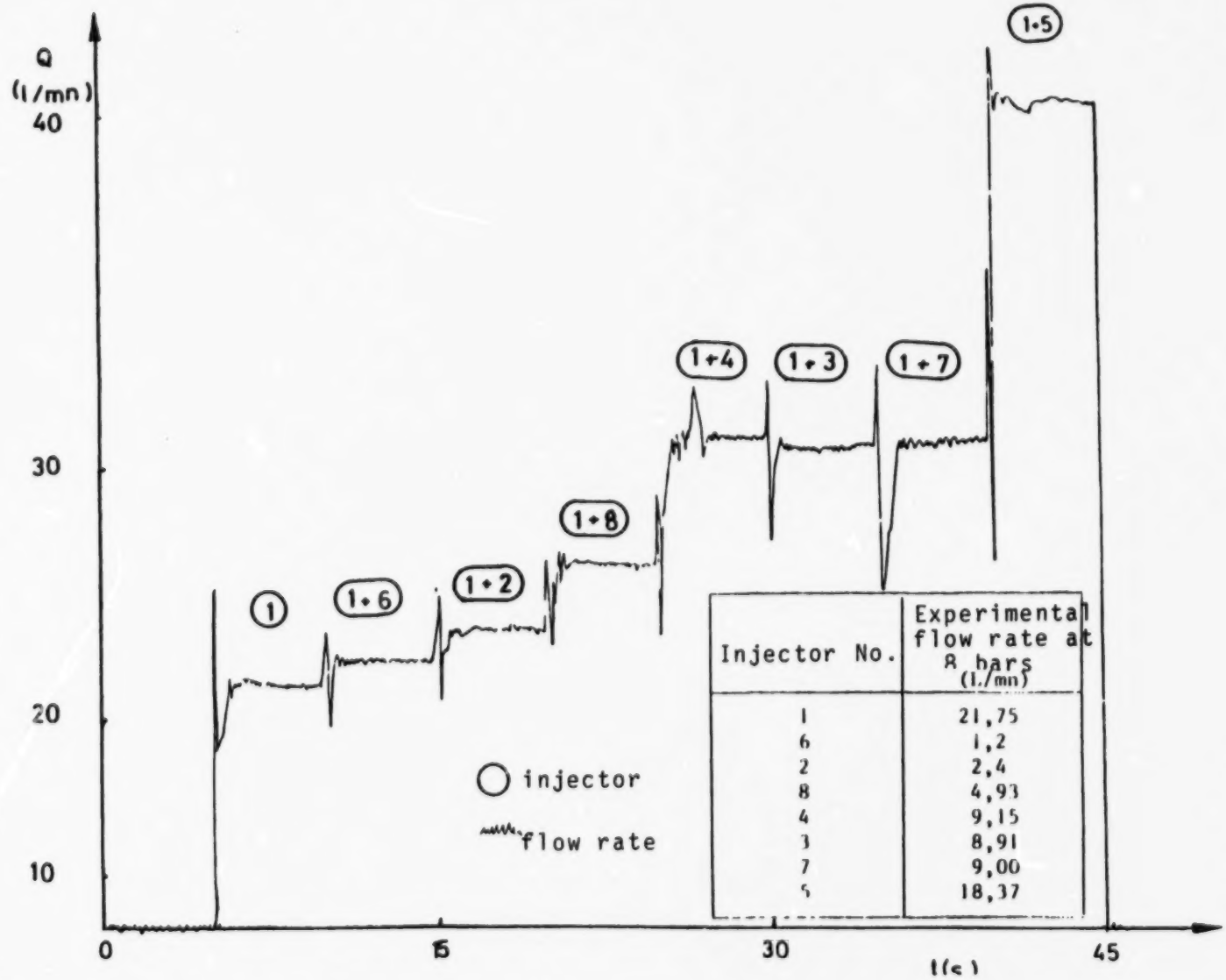



Fig. 9. Transfer function of the injection system




| Injector No. | Experimental flow rate at 8 bars (l./mn) |
|---|---|
| 1 | 21,75 |
| 6 | 1,2 |
| 2 | 2,4 |
| 8 | 4,93 |
| 4 | 9,15 |
| 3 | 8,91 |
| 7 | 9,00 |
| 5 | 18,37 |

Fig.10. Calibration curves of the injection system

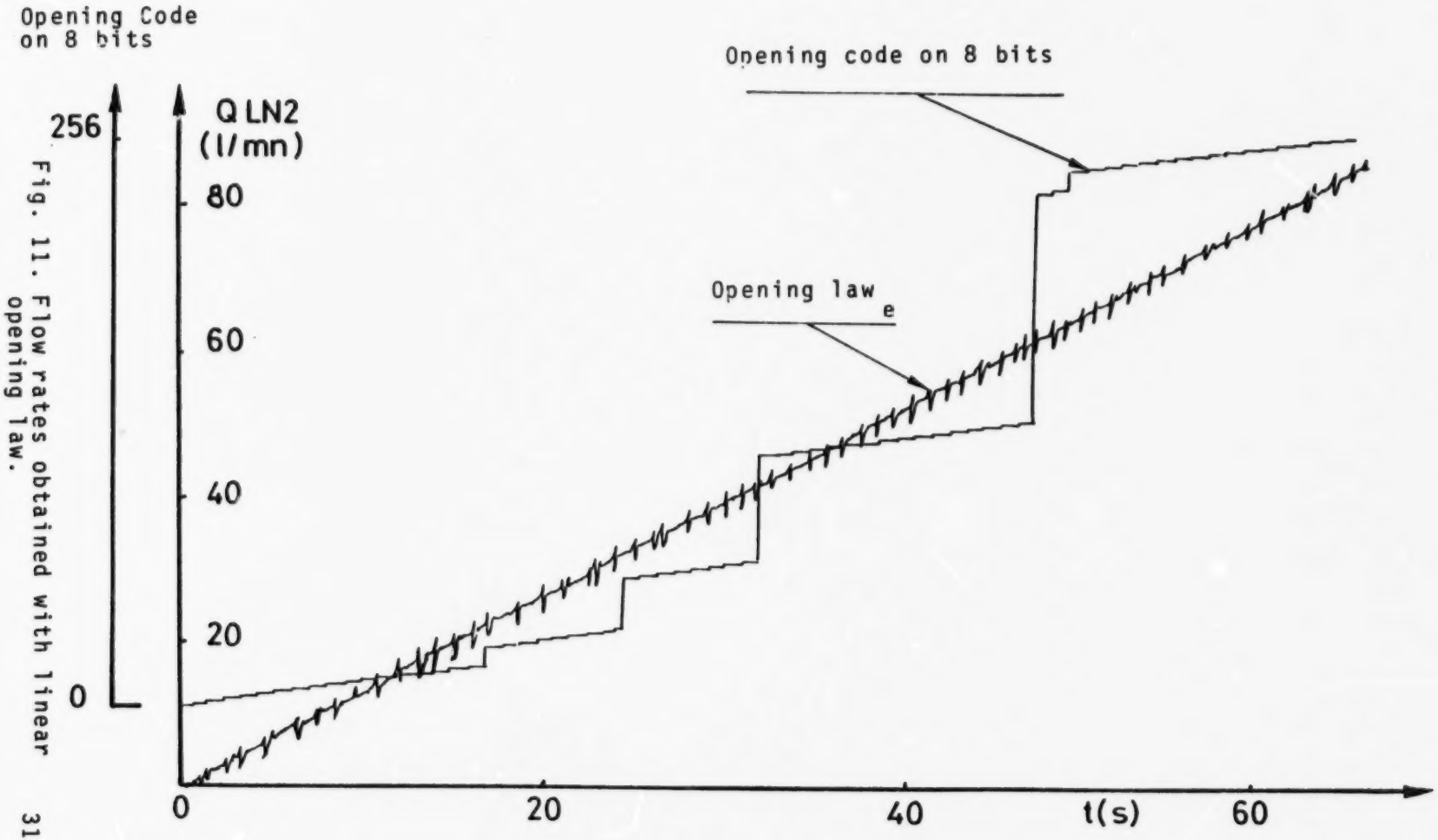



Fig. 11. Flow rates obtained with linear opening law.

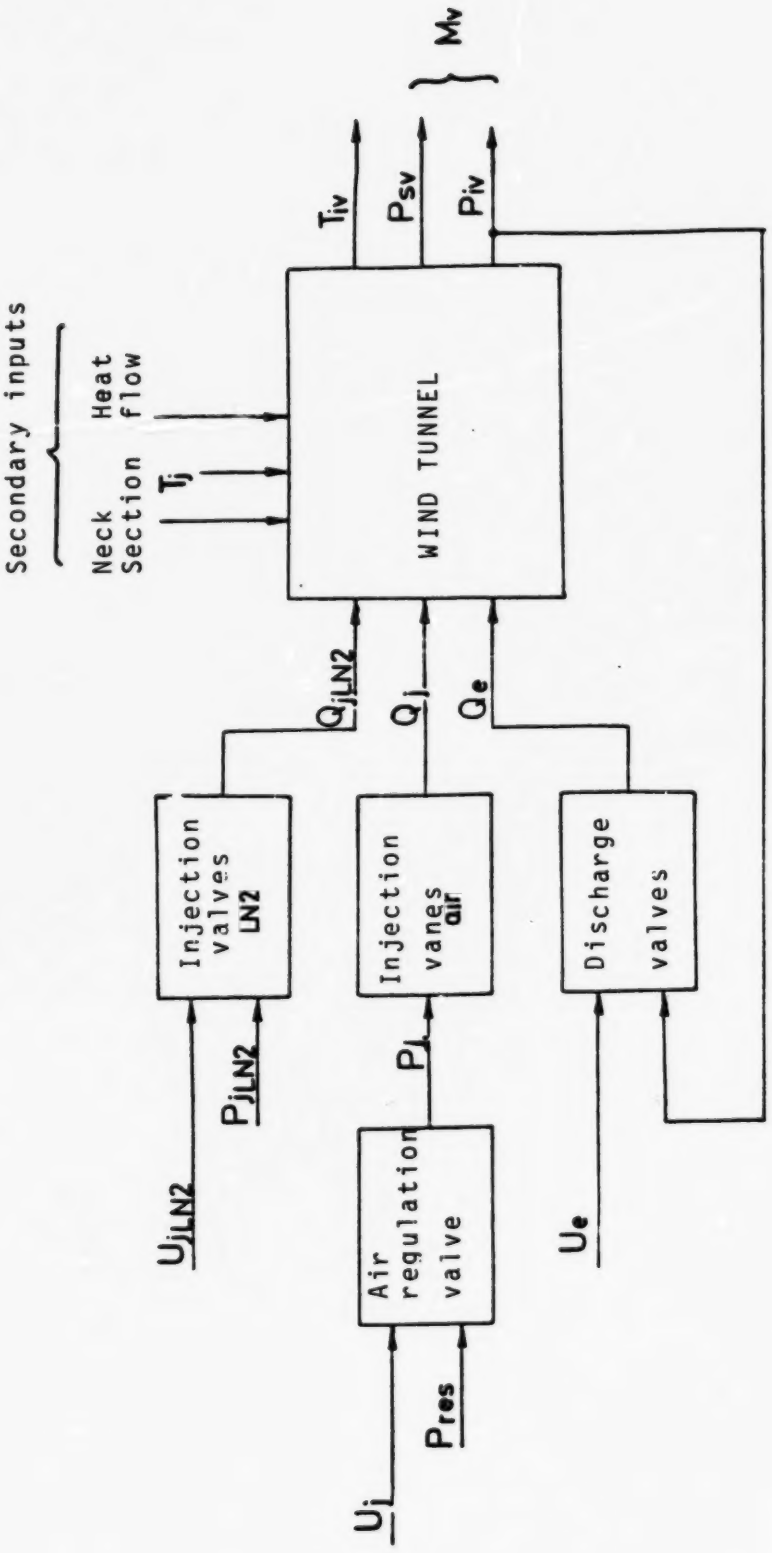



Fig. 12. Flow chart retained for illustrating wind tunnel control system

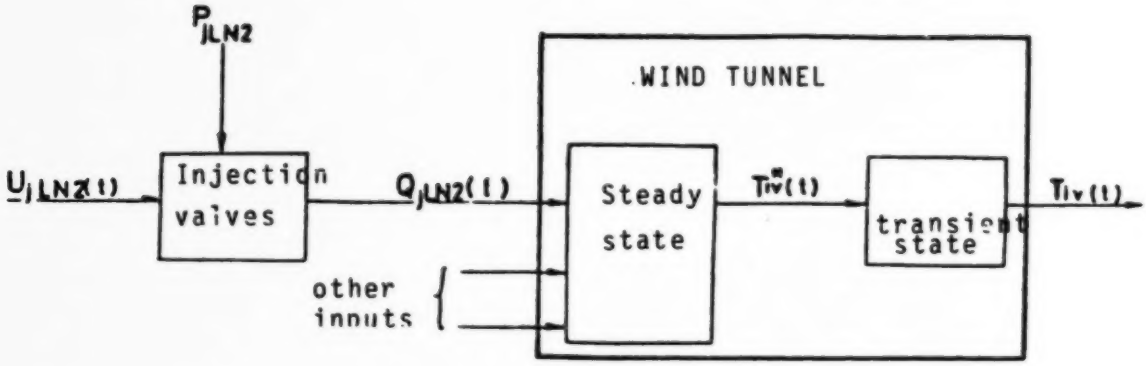



Fig.13. Simplified transfer function of the wind tunnel

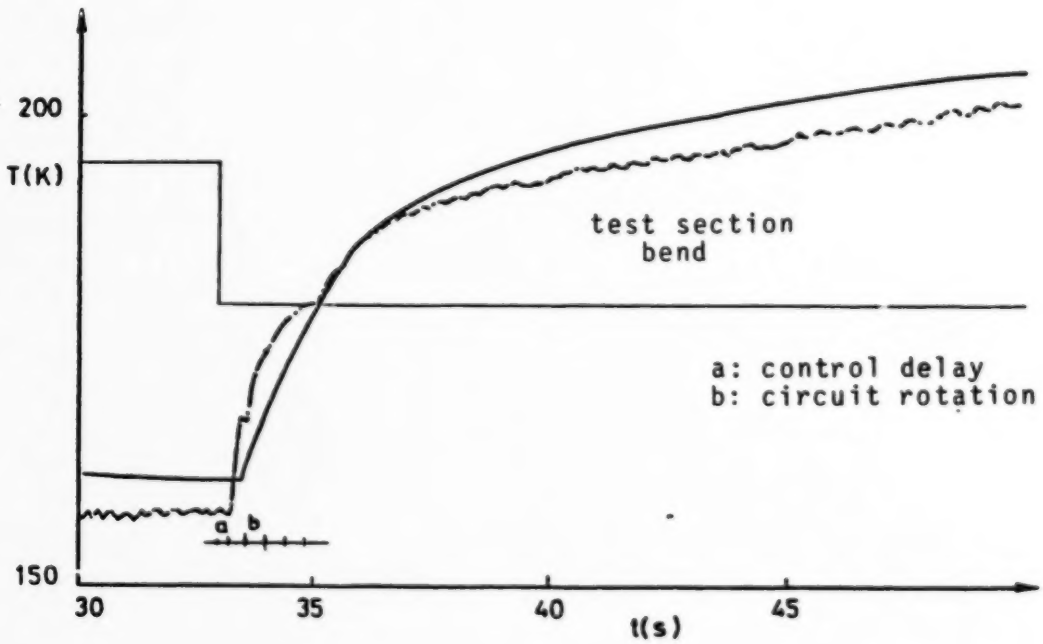



Fig.14. Response to a flow level of small amplitude

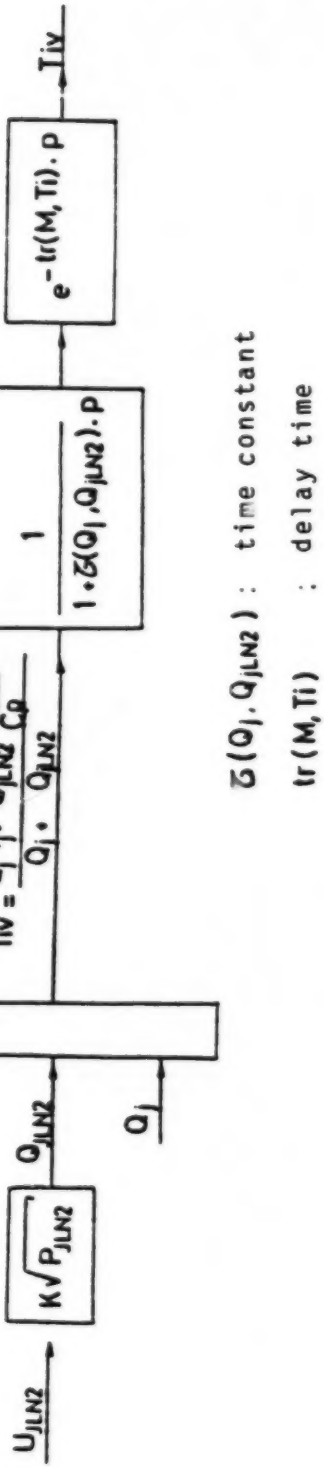



Fig.15. Transfer function used for representing the wind tunnel

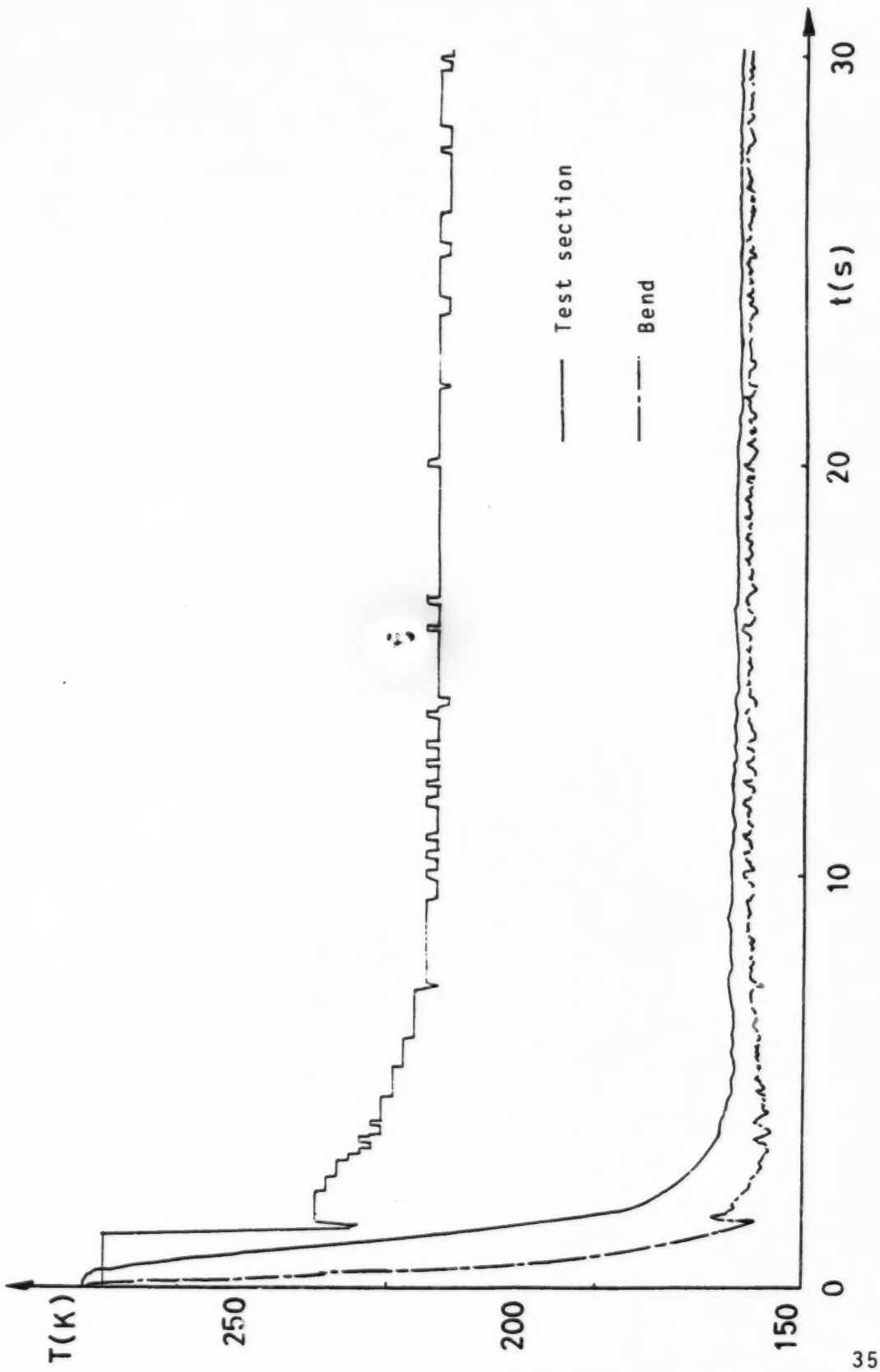





Fig.16. Close loop control using measurement in second bend.

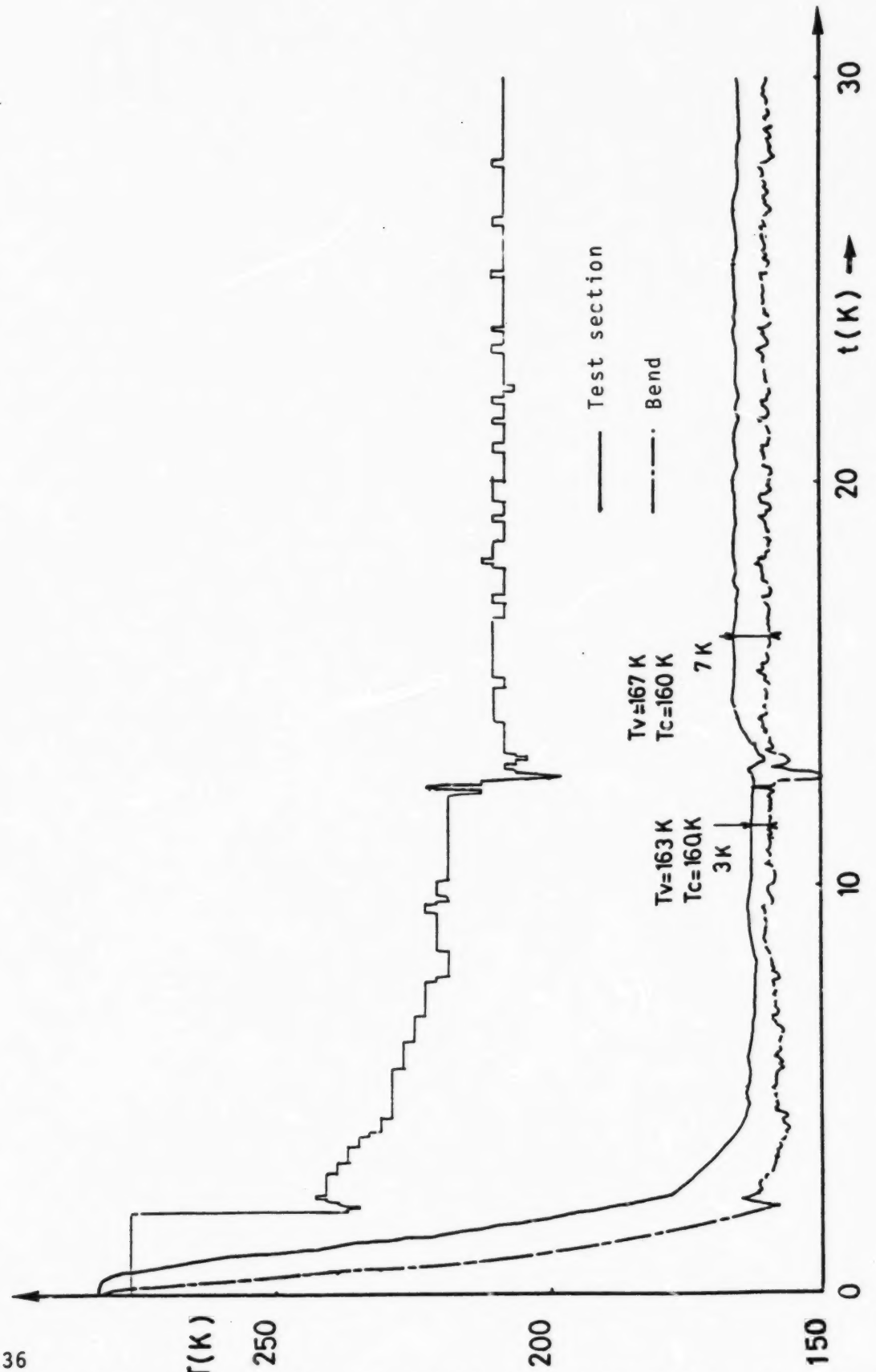



Fig.17. Demonstration of spatial distribution flaws in test section.

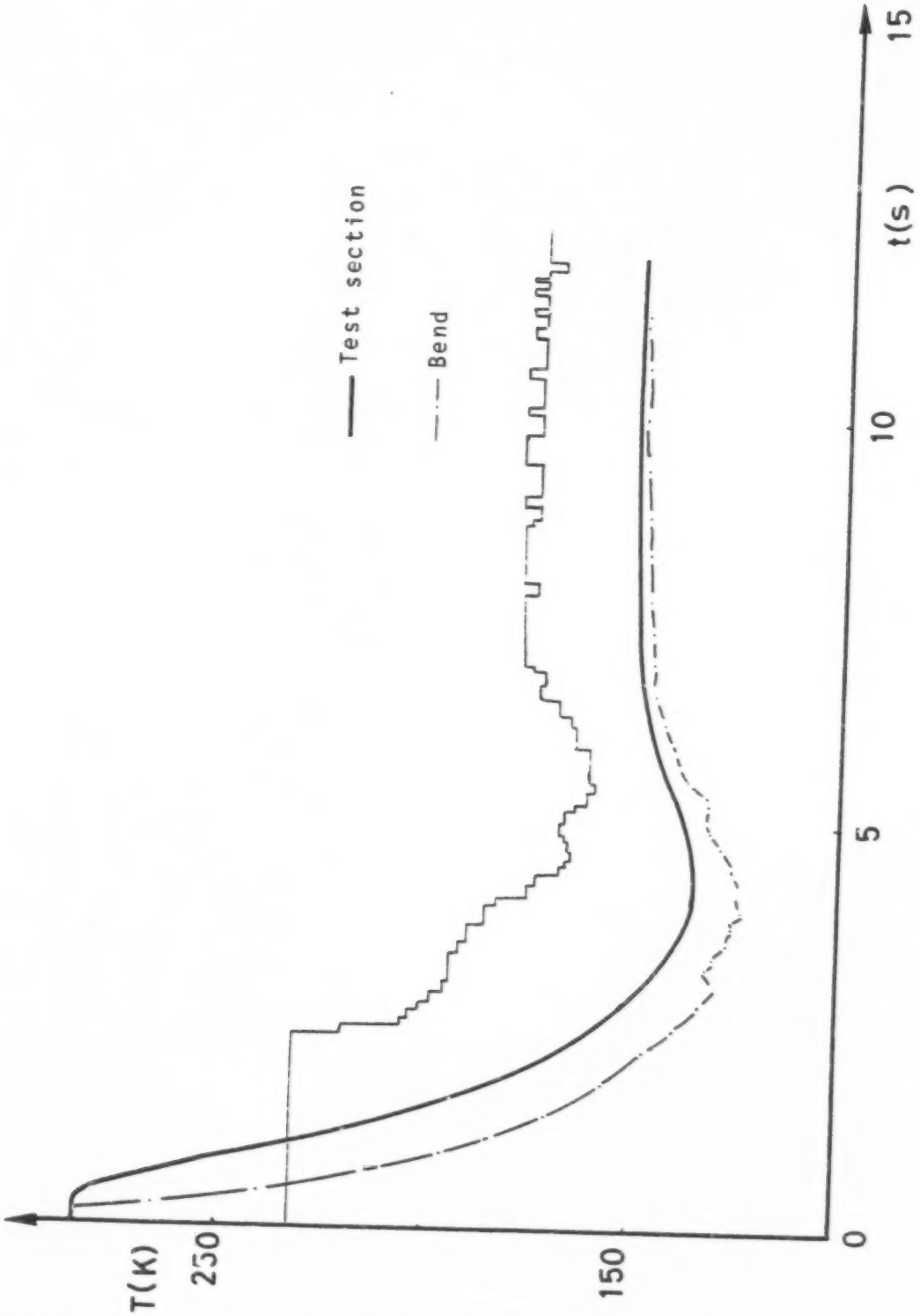



Fig.18. Regulation using test section temperature

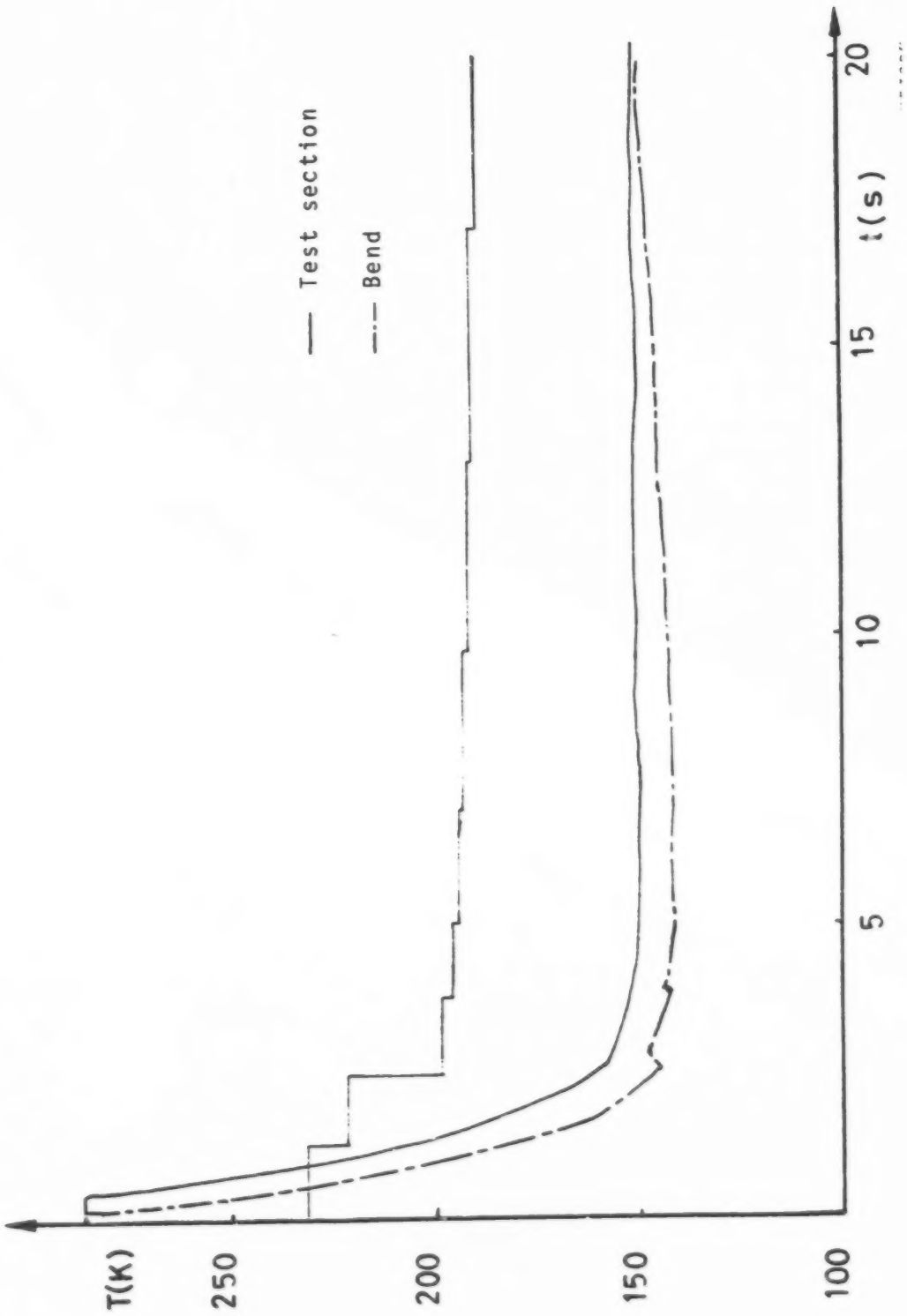



Fig.19. Improving temperature control by increasing the sampling cycle and prediction of error signal and its derivative.